

# **Final Report**

**The Syracuse University Center for Training  
and Research in Hypersonics**

**1 August 1993 – 31 January 2000**

**NAGW – 3713**

Submitted to the

**National Aeronautics and Space Administration**

Langley Research Center

18 July 2000

Submitted by:

**Prof. John LaGraff**  
Syracuse University, Syracuse, NY, USA  
+1-315-443-1189  
jlagraff@ecs.syr.edu

# 1 Overview

In the Summer of 1993, in response to a national solicitation of proposals, three centers of excellence in hypersonics were established by the Office of Aeronautics of NASA Headquarters. Syracuse University was one of these three. The five year proposal request was initially funded for three years beginning August 1, 1993. Progress reports for the first three years were filed with our Technical Monitor in The Office of Aeronautics. Early in the fourth year of the grant, we were notified that the final two years of the five year proposal would not be funded. A transition period was negotiated to accommodate students already obligated, but plans to wind down the activities of the Center were undertaken. Eventually, no-cost extensions of the residual funds (direct and cost-sharing) carried the program to January 31, 2000. The focus of the original proposal was to create an environment to stimulate student interest in the field of hypersonics by various incentives. The focus of this report is on the students who were engaged in one way or another with the activities of the Syracuse University Center for Hypersonics.

## 2 Introduction

In Fall 1993, NASA Headquarters established Centers for Hypersonics at the University of Maryland, the University of Texas-Arlington, and Syracuse University. These centers are dedicated to research and education in hypersonic technologies and have the objective of educating the next generation of engineers in this critical field. At the Syracuse University Center for Hypersonics this goal is being realized by focusing resources to:

- Provide an environment in which promising *undergraduate* students can learn the fundamental engineering principles of hypersonics so that they may make a seamless transition to graduate study and research in this field,
- Provide graduate students with advanced training in hypersonics and an opportunity to interact with leading authorities in the field in both research and instructional capacities,
- Perform fundamental research in areas that will impact hypersonic vehicle design and development.

Undergraduate instruction in courses directly relevant to hypersonics is being used to provide a foundation for graduate training and to enable undergraduate research in the field. Course instruction includes topics such as hypersonic gas dynamics, high-temperature materials, hypersonic vehicle design issues, and computational science. Undergraduate research has been used successfully at Syracuse University (particularly under the auspices of the National Science Foundation) to provide an impetus for outstanding students to attend graduate school. This practice has been extended to hypersonics, with students working alongside faculty and graduate students on a variety of hypersonic fluid dynamic and materials problems. Promising undergraduates are also being placed in co-operative engineering education work blocks with industry and government in the field of hypersonics.

Graduate education consists of classroom instruction, interaction with leading hypersonics researchers, and experimental and computational research both at Syracuse University and at government laboratories. The graduate training is centered on *fundamental* research so that students are prepared to contribute to a broad range of problems upon completion of their dissertations. The instruction and research are focused on three areas of importance in hypersonics: turbulent hypersonic flows, high-temperature composite materials, and the application of high-performance computing to computational hypersonic fluid dynamics and propulsion. Students and faculty working within the Syracuse Center are collaborating with scientists at NASA-Langley, NASA-Lewis, USAF Wright Laboratories, Calspan ATC, GASL, and Naval Surface Warfare Center to take advantage of unique national facilities and to expose students to leaders in the field.

### 3 Undergraduate Instruction

In an attempt to organize course offerings and stimulate student interest in hypersonics, the Department of Mechanical, Aerospace, and Manufacturing Engineering has instituted a "hypersonics certificate" program. The certificate is earned during the final two years of undergraduate study and it signifies that the recipient has completed a concentration of four courses in areas directly related to hypersonics. Each student must complete *Compressible Fluid Mechanics*, perform guided research in hypersonics, and must select two additional undergraduate courses from: *Composite Materials* (which includes material on ceramic- and metal-matrix composites), *Elements of Hypersonic Flight*, *Computational Fluid Dynamics* (which includes material on supersonic and hypersonic flows), and a second hypersonics research project.

#### **3.1 Fluid Dynamics /Propulsion**

The standard fluid dynamics course sequence in the Syracuse aerospace engineering program is: *Fluids I*, *Aerodynamics* (low-speed), *Compressible Fluid Mechanics*, and *Propulsion*; senior technical electives include *Rocket Propulsion*, *Computational Fluid Dynamics*, and the new *Hypersonics and High- Temperature Gas Dynamics*. An introduction to hypersonic flows is provided in the compressible flow course, with an emphasis on the physical differences in the flowfield at very high Mach number. Airbreathing engine cycle analysis and component analysis for a hypersonic vehicle with an integrated scramjet engine are covered in the aerospace propulsion course. Key issues and challenges in the design of the inlet, combustor, and nozzle for such a vehicle are discussed, with the open-ended design of a scramjet combustor serving as the term project. *Hypersonics and High- Temperature Gas Dynamics* is a survey course, and consists of the following topics: the hypersonic environment, hypersonic vehicle trajectory analysis, inviscid hypersonic gas dynamics, hypersonic viscous effects, introduction to high-temperature materials, and hypersonic vehicle design considerations. Enrollment for this elective course has typically been between 10 and 15 students.

#### **3.2 High-Temperature Materials/ Structures**

Polymer-matrix composites have traditionally been emphasized in the undergraduate composite materials course at Syracuse University. This course has been revised to include material composites for hypersonic applications. Sections were added to the course that covered high-temperature composite materials and material and structural technology challenges for hypersonic vehicles. Various structural configurations that have been proposed for hypersonic vehicles were discussed, as was the role of material selection, and how both the material and structural configuration affect performance and economic viability. Other applications of high-temperature composites, such as in automobile engines and gas turbines, were also discussed.

## 4 Undergraduate Co-operative Education

An important component of the Syracuse Center for Hypersonics is the co-operative education opportunities that have been made available in the field of hypersonics. Promising undergraduate students have been placed in hypersonics co-op positions at NASA Lewis, NASA Langley, Calspan ATC, Naval Surface Warfare Center (NSWC), and the General Applied Science Laboratories (GASL). These particular placements have been selected because the co-op students are able to interact with leading authorities in hypersonics while learning to conduct fundamental research in the field. The co-op students are typically involved in hypersonics research at Syracuse when they return from their work blocks. NASA HQ support has not been used for these co-op placements; rather, other leveraging support has been obtained from: the Cornell/New York State Space Grant Consortium, the Navy, NASA Lewis, Calspan ATC, and GASL.

Summary capsules of the co-op work assignments are given below:

- **NASA Glenn.** The focus of these assignments has been the use of mechanical and nondestructive testing techniques on ceramic matrix composites, particularly silicon carbide reinforced reaction bonded silicon nitride (SiC/RBSN). The co-op student learned to use acoustic emission analysis to locate and quantify damage during mechanical testing, x-ray radiography to nondestructively evaluate damage, and metallography to corroborate the nondestructive results.
- **NASA Langley (Hypersonic Propulsion).** This assignment involved the conversion of an existing quasiID explicit CFD code for reacting flows to a semi-implicit one to improve the convergence rate. The physical problem was an examination of the unsteadiness of detonation wave structure along the stagnation line of a ballistic body in hypersonic flow.
- **NASA Langley (Quiet Tunnel Testing).** This co-op work block consisted of experimental work in preparation for the new Langley Mach 8 quiet tunnel. Specifically, the student constructed a test hot-flow facility and examined a variety of experimental techniques to ascertain their usefulness for instrumenting a hot quiet tunnel flow.
- **NSWC.** The co-op student at the Naval Surface Warfare Center (Dahlgren Site) has been involved in the evaluation of instruments for measuring instantaneous heat transfer in a high-enthalpy Mach 7 transient tunnel test.
- **Calspan.** The assignment with Calspan's hypersonics group involved the development of numerical solutions to a 2-D unsteady heat transfer problem associated with transient hypersonic testing. The solutions were used to account for non-linear effects in the extraction of instantaneous heat transfer rates from wide-bandwidth surface thin-film resistance thermometers.
- **GASL.** The GASL research experience focused on a variety of hypersonic testing techniques in both their HYPULSE and blowdown facilities. The student was exposed to heat transfer gauge technology, piezoelectric pressure transducers, and schlieren flow visualization.

## 5 Undergraduate Research and Co-Op

The Department of Mechanical, Aerospace, and Manufacturing Engineering holds a site grant from NSF for a 12-week summer research program focused solely on fluid dynamics. A different NSF grant sponsors undergraduate research in advanced composite materials suitable for hypersonic applications. Still other students perform hypersonics research as part of their senior honor's thesis or as an independent study. All of these programs provide a comprehensive graduate-school-type experience for promising undergraduates ranging from freshmen to seniors. The research experiences are based around one-on-one interaction between the undergraduate students and their faculty mentors, with emphasis on development of research skills, critical thinking ability, and communication skills. Historically, the vast majority of the students participating in these research programs continue on to graduate school; several of the participating students are now focusing their research efforts in areas related to hypersonics. Table 1 summarizes the various hypersonic research projects performed by undergraduate students.

Student	Project
Ajay Chawan	Fracture mechanics of advanced composite materials
Erik Christiansen	Optimization of scramjet lobed-mixer fuel-injection strut
Erwin Chung	Optimization of scramjet lobed-mixer fuel-injection strut
Kimberly Clowe	Hypersonic WWW server
Ryan Hudson	Delamination toughness of fiber-reinforced composites
Christopher Joe	Analysis of Mach 11 turbulence data
Timothy O'Brien	Hypersonic compression ramp shock/boundary layer interactions
Ryan O'Grady	Design of a hypersonic nozzle
Jonathan Polaha	Delamination toughness of fiber-reinforced composites
Erica Sanders	Hypersonic WWW server
Daedra Studniarz	Hypersonic fuel-injection strut experiments

Table 1: Undergraduate hypersonic research projects.

Details of these undergraduate research projects are provided below:

- **Fracture mechanics of advanced composite materials.** Students have performed delamination growth experiments using polymeric and ceramic matrix composite test specimens. The research involves manufacture and testing of a variety of different specimens, and determination of delamination toughness. Data is being compared to predictive theories being developed in the Syracuse Center.
- **Analysis of Turbulence Data.** Wavelet transforms are being used to analyze turbulence data from hypersonic boundary layers. Wavelets have been shown to be excellent tools for characterizing turbulent boundary layers, and one undergraduate project involves the wavelet analysis of Mach 11 helium boundary layer data with the intent of identifying compressibility effects.
- **Transient Hypersonic Tunnel Design.** Modifications have been made to an existing Ludweig-tube facility to provide a hypersonic testing capability. Undergraduate students assisted in the design of the nozzle and test section, using CFD to verify the nozzle design and CAD to develop the design drawings.
- **Hypersonic WWW Server.** Undergraduate students are developing a WWW server for the NASA/Syracuse Center for Hypersonics. The focus of their research to date has been two-fold: 1.) creation of the hyperlink environment, and 2.) incorporation of Syracuse Center results. It is hoped that hypersonic educational materials for undergraduates will be developed on the WWW.
- **Hypersonic Compression Ramp Shock/Boundary-Layer Interactions.** An experimental study is being performed to gain insight into the shock-wave/boundary-layer interaction created by a compression corner. The experiment is being performed in a transient Mach 6 tunnel, with several different ramp angles and means to create controlled shock unsteadiness. The primary means of measurement is an array of flush-mounted heat-transfer gauges.

- **Optimization of Scramjet Lobed-Mixer Fuel-Injection Strut Geometries.** In this study, undergraduates are working on a new hypermixer fuel-injection strut that can be readily incorporated into the basic NASA Langley scramjet engine. The proposed fuel-injection strut enhances mixing via the lobed mixer concept employed in conventional turbofan engines. The preliminary computational study using an inviscid model indicates that this mixing enhancement concept is very promising.
- **Experimental Study of Fuel-Injection Struts in Hypersonic Flow.** This experimental study is complementary to the main CFD study of lobed-mixer strut geometries. Supporting data will be gathered for the baseline diamond-shaped strut and simple lobed-mixer geometries.

## 6 Graduate Instruction

### 6.1 Hypersonics Seminar Series

Beginning in 1994-95, an important element of the Center for Hypersonics has been a graduate seminar series designed to expose the undergraduate and graduate students to scientists and engineers working in the field.

Invited Speaker	Affiliation	Research Area
Jacob Aboudi	Technion	Materials
Iain Boyd	Cornell	Low-density hypersonic flows
David Caughey	Cornell	CFD techniques for high-speed flows
Ray Edelman	Rocketdyne	Hypersonic air-breathing combustors
John Erdos	GASL	Hypervelocity test facilities
Michael Holden	Calspan ATC	Hypersonic testing
John LaGraff	Syracuse	Ransient testing techniques
Mark Lewis	Maryland	Waverider aerodynamics
Lyle Long	Penn State	Parallel algorithms for rarified gas dynamics
Steven Wander	NASA HQ	Recent history of hypersonic research
William Yanta	NSWC	Hypersonic research at NSWC

Table 2: Invited speakers at the graduate hypersonics seminar series.

### 6.2 Fluid Dynamics

Three courses directly relevant to hypersonic fluid dynamics research are now offered at Syracuse: *Advanced Thermodynamics II*, *Hypersonic Gas Dynamics*, and *Computational Fluid Dynamics*. The advanced thermodynamics course is focused on molecular processes, particularly in high-temperature and high-velocity gases. Classical kinetic theory of gases and statistical thermodynamics are covered, providing sufficient background to understand thermodynamics and transport phenomena in gases. The depth of coverage is equivalent to that provided in texts such as "Physical Gas Dynamics" (Vincenti & Kruger).

*Hypersonic Gas Dynamics* provides an introduction to the physics of hypersonic flows and high-temperature gas dynamics, analytical methods for describing and evaluating the associated phenomena, and experimental methods for probing such flows. Classical inviscid hypersonic theory and hypersonic viscous flow are covered, including hypersonic effects on transition and turbulence. The existence of the advanced thermodynamics course also allows coverage of non-equilibrium high-temperature gas dynamics. The recent texts by Anderson and Rasmussen are used extensively, and additional depth is provided with readings from Chernyi, Cox & Crabtree, Hayes Probststein, and Dorrance.

The CFD course is newly revised and now provides an emphasis on the development of finite-volume based CFD codes to simulate high-speed flows for complex geometries. The course introduces a variety of numerical schemes used to compute inviscid and viscous hypersonic flows and flows with high-temperature effects. A portion of the course focuses on implementation of modern schemes on high-performance parallel-architecture computers. The instructor (Prof. T.Q. Dang) has authored a monograph based on the course material, and planning is underway to make this text available on the World-Wide Web.

### **6.3 Solid Mechanics & Materials**

A new section was added to the existing course *MEE 625 Fracture Mechanics* that covered the fracture mechanics of high-temperature composite materials. Included in this section was treatment of metal-matrix composites, ceramic-matrix composites, and other advanced high-temperature materials. Detailed discussion of thermal and mechanical environments, and material and structural failure modes were presented.

### **6.4 High-Performance Computing**

Computational Science is a discipline emerging at the interface of Computer Science and application disciplines, including engineering and the sciences. In Fall 1992, Syracuse University introduced a curriculum in computational science for graduate students. M.S.- and Ph.D.-level "Certificates in Computational Science" recognize that a student has acquired knowledge about computing, computational techniques, and how to apply them in a primary field of study. The Syracuse Center for Hypersonics interacts with the Syracuse Computational Science (CPS) curricula in two distinct fashions. Directly, the new course in computational hypersonics will satisfy discipline-specific computational requirements, where it will join courses in computational physics and neuroscience under development. However, the core of the CPS curricula consists of three general courses that cover a range of practical computer science issues, numerical analysis, and algorithms and software arranged as modules covering particular topics. CPS-500 and CPS-615 spend approximately three lectures on each module and differ in emphasis on parallel computing. CPS-500 uses Fortran90 and C++ but is centered on the use of modern workstations; CPS-615 is centered on parallel machines. CPS-713 goes through three modules in greater detail; this year these were computational fluid dynamics, data analysis and statistics, and Monte Carlo methods. The CFD module was based on classical algorithms, several of which have been defined concisely as the NAS parallel benchmarks. Computer science material on parallel PDE solvers also was included. The approach allowed non-aerospace majors to study the computational science issues in "real CFD problems." In the hypersonics application, the computational hypersonics course described earlier will be integrated into modules for use in these three key CPS courses.

## **7 Faculty & Graduate Student Research**

### **7.1 Graduate Student Researchers**

Table 3 provides a summary of the graduate student contributors to the mission of the NASA/Syracuse University Center for Hypersonics.

### **7.2 Turbulent Hypersonic Flows**

The advanced technologies needed to achieve national goals in hypersonics cannot be developed without research on the character and dynamics of hypersonic turbulence. For example, an examination of the critical issues in two of the major hypersonic disciplines, aerodynamics and propulsion, reveals a variety of flow phenomena in which turbulence plays a significant role:

<b>Student</b>	<b>Support</b>	<b>Status</b>	<b>Research Area</b>
Ajay Bhandari	Syracuse TA	2nd-year M.S.	CMC materials
Carl Blake	Syracuse TA	1st-year M.S.	TBD
Raesh Bordaewekar	NPAC support	Ph.D. candidate	high-performance computing
Mario Campuzano	NASA GSRP	2nd-year M.S.	hypersonic mixing
Paul Cataldi	Syracuse TA	Completed M.S.	hypersonic facility design
Kedar Hardikar	Syracuse TA	1st-year M.S.	TBD
Ricardo Hassan	Syracuse TA	1st-year M.S.	TBD
Mike Kegerise	NASA RA	completed Ph.D.	hypersonic turbulence
James Mazzaella	Self	Ph.D. candidate	high-performance computing
Laurie Nill	Syracuse Fellow	Ph.D. candidate	hypersonic turbulence
Jonathan Polaha	NASA RA	1st-year M.S.	CMC materials
Xuwen Qiu	Syracuse Fellow	Ph.D. candidate	supersonic simulations
Kevin Roe	NASA RA	2nd-year M.S.	high-performance computing
Deo Sabino	Syracuse TA	2nd-year M.S.	CMC materials
Michael Sealy	Syracuse Fellow	2nd-year M.S.	DSMC of rarefactions
Mark Sheplak	NASA GSRP	Completed Ph.D.	hypersonic turbulence
Tor Sherwood	Syracuse TA	1st-year M.S.	CMC materials
Rajeev Thakur	NPAC support	Completed Ph.D.	high-performance computing
Yu Wang	Syracuse Fellow	Ph.D. candidate	transient testing

Table 3: Graduate students affiliated with the NASA/Syracuse Center for Hypersonics.

- Separated and vortical flows,
- Control-surface flows (pressure gradients and streamline curvature),
- Shock-wave/boundary-layer interactions,
- Transition prediction (ground-test facility validation),
- Low-loss fuel/air mixing,
- Shock/shock interactions,
- Boundary-layer ingestion.

In an effort to perform research of practical significance and to provide graduate student training that is of lasting value, the Syracuse Center is focusing on the fundamental turbulent nature of these flows. Experimental research is being performed in a transient facility at Syracuse University and in hypersonic wind tunnels at NASA-Langley Research Center.

While very limited turbulence data exist for the complex flows listed above, the lack of knowledge of hypersonic turbulence even extends to the simple case of a zero-pressure-gradient boundary layer. Existing turbulence models for this canonical flow are based on incompressible models, with compressibility modifications that are generally believed to be dubious at Mach numbers above 5. Physically, we expect hypersonic boundary-layer turbulence to be significantly different than that at supersonic Mach numbers because of several factors: the extreme viscous dissipation near the wall, the increased importance of pressure fluctuations, the probability of supersonic relative velocities between organized motions and high-speed entrained fluid, and perhaps even the very different nature of transition at hypersonic Mach numbers.

In an attempt to characterize high-Mach-number turbulence, a series of measurements were made in a Mach 11 helium boundary layer in a NASA-Langley/Syracuse collaboration. The turbulence measurements were made via constant-temperature hot-wire anemometry, and the frequency response was maintained at a value greater than 400 kHz (10U,16). The resulting wide-band power spectral density distributions are smooth and highly repeatable, and may enable spectral scaling laws to be extended to higher Mach number. The r.m.s. mass-flux fluctuations show clear differences with lower Mach-number supersonic flows, exceeding 50% of the local mean mass flux in the middle of the boundary layer. Comparisons made between the turbulence data obtained at two Reynolds numbers indicate possible Reynolds-number effects in the lower portion of the boundary layer. A comparison to subsonic and supersonic data reveals clear differences in the higher-order moments of the fluctuations.

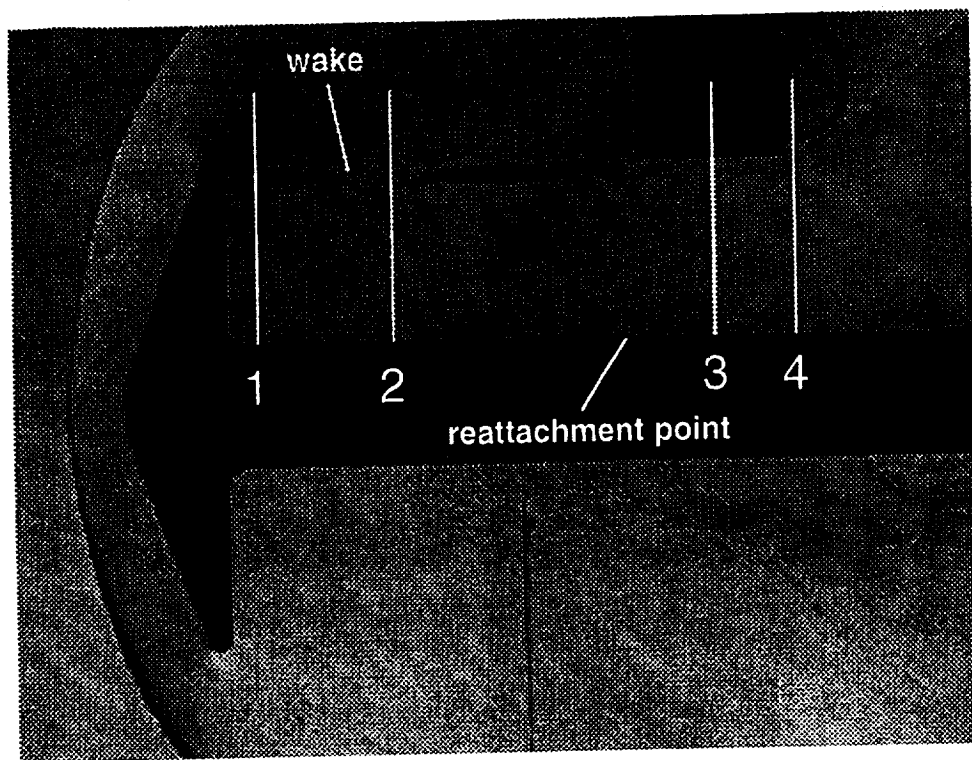


Figure 1: Schlieren photograph of the hot-film probe traversing through the wake of a 70° blunted cone.

While the Mach 11 helium tests are useful for examining some features of high-Mach-number turbulence, their applicability to real hypersonic problems is limited due to the low-enthalpy nature of the flow ( $T_o = 300$  K). The demands on a turbulence measurement system in a realistic hypersonic environment are severe due to elevated stagnation enthalpies and high dynamic pressures. Hot-wire anemometry can withstand neither the high temperatures nor the high dynamic pressures of hypersonic *air* flows at Mach numbers as low as 6. Non-intrusive measurement techniques are limited by flow-seeding concerns such as biasing and data rate. In another collaboration with NASA-Langley engineers, Syracuse University investigators have developed a hot-film anemometry technique that is promising for many hypersonic flows. The hot-film probe is superior for hypersonic flow due to sensor placement, the use of high-temperature materials, and state-of-the-art microphotolithographic fabrication techniques. Tests in Mach 11 helium and Mach 6 air flows have been very promising, with a probe frequency response that is a factor of five higher than that of previous hot-film sensors. The current probe design is appropriate for testing in air to Mach numbers of about 8, but is limited to *qualitative* instantaneous information until questions about the dynamic response can be answered.

If the hot-film probe can be properly characterized, it will be used to explore the effect of perturbations on hypersonic turbulent shear layers, including boundary layers, wakes, and mixing layers. There are a range of important fundamental and applied research issues in this area related to the design of propulsion inlets, combustion chambers, and control surfaces for hypersonic vehicles. The hot-film probe would be particularly useful in these flows since hot wires generally cannot survive due to the strength of the perturbations and the high turbulence levels.

An example of the usefulness of the hot-film probe is an experiment that we conducted at NASA Langley during Summer 1995. Detailed qualitative fluctuation surveys were made in the wake of a 700 half-angle spherically blunted cone possessing a cylindrical afterbody. Measurements on this 5.75% scale model of the aerobraking surface of the Mars-Pathfinder were performed in the NASA-Langley 20-inch Mach 6 facility (see Figure 1). During entry to the Mars atmosphere, the flow will separate at the forebody shoulder, creating a free shear layer in the near-wake region. Attention is focused on aerodynamic heating in this region of the flowfield because the instrumentation payload is located in the base region. The state of the wake (laminar vs. turbulent) will strongly influence the nature of the heat transfer to the afterbody. The hot-film probe was used to take measurements in portions of the wake where the conditions were such that hot wires could not survive (due to a combination of stagnation quantities, dynamic pressure loads and high fluctuating levels). The flow fluctuations in the wake were characterized at several different stations (marked 1-4 in Figure 1), and a complete map of laminar and turbulent regions was obtained.

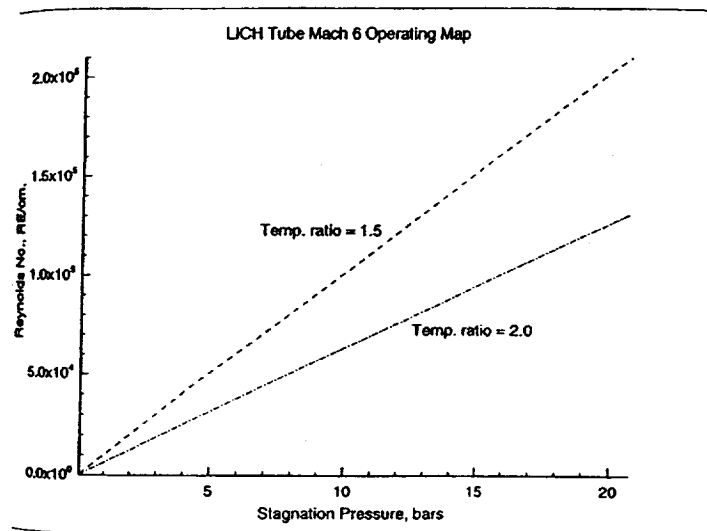


Figure 2: Operating map for the Syracuse University LICH tube with Mach 6 nozzle.

Although much of the experimental aerodynamic research associated with the Syracuse Center for Hypersonics involves major national facilities, some in-house capability exists: a new Mach 6 axisymmetric open-jet nozzle has been constructed for an existing Ludweig tube facility. The facility uses a single-stroke piston compression process to heat the working gas isentropically. This produces temperatures of up to 600 K at pressures of 10-20 atmospheres (see Figure 2). The facility, referred to as a LICH tube (Ludweig tube with Isentropic Compression Heater), was originally used for lower subsonic and supersonic aerodynamic and heat transfer research related to gas turbine internal flows. With the new nozzle and test section, run times on the order of 70 milliseconds at Reynolds numbers of up to  $2 \times 10^5 \text{ cm}^{-1}$  can be produced. Although the isentropic compression mode of gas heating produces relatively modest enthalpy levels (compared to shock heating of gases), there are a variety of useful fundamental tests that can be performed in this facility. One area of immediate interest being undertaken is a study of unsteady heating in the region of strong shock/boundary-layer interactions, especially those associated with scramjet nozzle inlets. Another area of considerable interest that will be studied in this facility involves the fuel injection and mixing process in scramjet combustors. This will be done in collaboration with the CFD modeling study of mixing described below. A final area of research activity is in hypersonic transition studies. Preliminary efforts will focus on the 3-D turbulent spot breakdown process in the end-stages of transition. Since the end-stage transition process is less sensitive to acoustic radiation, it is not inappropriate to utilize a tunnel that is not acoustically "clean." The physics of the breakdown process should be well understood before the inlet compression ramp flow process can be optimized.

### 7.3 Computational Fluid Dynamics

During the second year, research in Computational Fluid Dynamics and High-Performance Computing & Communications for the NASA/Syracuse Center for Hypersonics has been concentrated in three areas:

1. enhanced fuel/air mixing strategies for scramjet engines,
2. effects of rarefaction on a continuum solution,
3. implementation of CFD codes on parallel computers.

The projects in these areas are briefly summarized below:

- **Numerical study of a lobed-mixer fuel-injection strut for a scramjet engine.** Fuel/air mixing enhancement strategies are extremely critical in the design of scramjet engine due to the inherently low

shear- induced mixing and short combustor residence time. In this study, we propose a new hypermixer fuel-injection strut that can readily be incorporated into the basic NASA Langley scramjet engine. The proposed fuel-injection strut enhances mixing via the lobed mixer concept employed in conventional turbofan engines. Our preliminary computational study using an inviscid model indicates that this mixing enhancement concept is very promising. Results for a scramjet combustor inlet Mach number of 3 indicate that the proposed hypermixer generates significant secondary flows for promoting rapid fuel/air mixing while the loss in stream thrust is small. Currently, the hypermixer is being evaluated computationally using the LARCK code developed at the NASA Langley Research Center. LARCK is a viscous CFD code with a capability to simulate high- speed combustion.

- **Streamwise vorticity injection in 3-D mixing layers.** In this project, the effect of spatial/strength distributions of streamwise vorticity injection on mixing in high-speed flows is being investigated. The goal of this project is to develop mixing enhancement techniques for SCRAMjet applications. In the initial phase of this investigation, a three-dimensional rectangular domain is being considered where, at the inflow boundary, streamwise vorticity is injected into the flow domain at the interface of the two streams. The algorithms employed to solve the Navier-Stokes equations include both second-order-accurate central and upwind schemes. Implementation of the computer code on sequential computers using Fortran 77 has been completed for the inviscid and viscous (laminar) flow regimes. Implementation of the Reynolds-averaged and LES version of the code is under way.
- **Simulation of supersonic mixing layers on massively parallel computers.** In this project, the 3D spatially developing mixing layer code described above is ported to parallel computers. This code is an ideal problem for implementing on parallel computers because of the enormous memory and computational time requirements. The code has been implemented using data partitioning and message- programming techniques on the Intel Touchstone Delta with up to 512 processors. Speedup in the computational time has been obtained by a factor of 14 going from 8 processors to 512 processors using a  $128 \times 64 \times 32$  mesh cells (a relatively coarse mesh, hence a relatively low efficiency of 0.22). The code is being converted from Fortran 77 to the new High Performance Fortran (HPF) language using the HPF compiler that is being developed by Portland Group Inc (PGI). HPF is a language for parallel computers that follows a set of standards that have been agreed at a recent High Performance Fortran Forum, and is being developed by a group of people from industry and academia. HPF achieves parallelism by distributing work among the processors. The user can specify the work distribution using the HPF data distribution directives, and these directives decompose the data among the processors. The HPF code is being tested using the computing facilities at (1) NPAC at Syracuse University, (2) NASA Ames, and (3) the Center of Advanced Computing Research (CACR) at Caltech. Massively-parallel computers employed in these calculations include the IBM SP-2, Intel Paragon, and DEC Alpha Cluster. During the development of the HPF code, we interacted extensively with the PGI group. We received valuable guidance's regarding HPF implementation while the compiler developers at PGI got feedback from us regarding the compiler performance. PGI has requested both the F77 and HPF versions of this code for use internally to validate their HPF compiler.
- **Implementation of TLNS3D using HPF.** In this project, an existing multigrid/multiblock CFD code that is extensively used in the aircraft industry (including Boeing and McDonnell Douglas) is being converted from Fortran 77 to HPF. The purpose of this work is to evaluate the performance of the new HPF language using a CFD code that is of practical use in the aerospace industry. During the course of this work, we have interacted closely with the HPF vendors. These interactions have yielded information on writing more efficient programs, and have aided the vendors in their attempt to create compilers that can handle critical issues (such as multiblock and multigrid) that arise in CFD applications. These discussions have contributed toward the development of the HPF language.
- **Analysis of the effects of rarefaction on a continuum solution.** The aim of the project is to analyze the effects of rarefaction on a continuum solution. To this end, a direct comparison will be made between continuum and direct-monte carlo simulations (DSMC for different Knudsen numbers spanning the continuum, transition, and free-molecule regimes. The case studies will consist of a Mach 10 axisymmetric; jet of argon impacting on a circular disk and a flat-nosed cylinder. The DSMC code limits the complexity of the models to a maximum of two flat surfaces which must be aligned with the axes. The temperature of the jet will be chosen so that ionization effects will not have to be taken into account. A finite volume approach will be used for the 2D/axisymmetric Navier-Stokes code. The time-marching scheme will make use of the Roe-Approximate Riemann method with an appropriate flux limiter. The constitutive relations for laminar

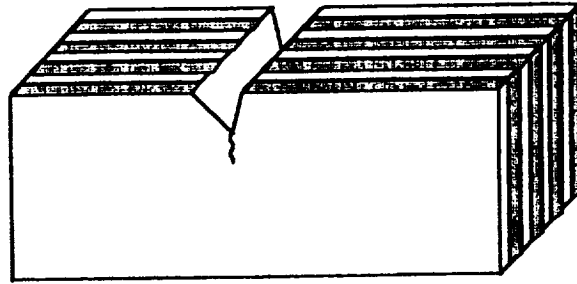


Figure 3: Laminated CMC fracture when crack front is perpendicular to the plane of lamination.

flow will be implemented first. It is expected that the continuum results will breakdown as soon as the this regime is breached. Therefore, a simplified translational nonequilibrium model (STNM) will be used for the constitutive relations. This model attempts to account for the discrete nature of gas and as such is expected to give better results outside the continuum regime. Based on the performance of the Navier-Stokes solver and the quality of the results, more complex geometries may be studied once a better DSMC code can be obtained.

#### **7.4 High-Temperature Materials and Structures**

The ability to use advanced materials, such as fiber-reinforced ceramics, metal matrix composites, or carbon/carbon in high-temperature structural applications would greatly improve the efficiency and viability of hypersonic vehicles. All of these materials have their individual benefits and drawbacks, and each is likely to be used in various capacities. The solid mechanics and materials faculty affiliated with the Center for Hypersonics at Syracuse University have chosen to concentrate on issues relating to fracture of laminated, bidirectionally reinforced ceramic matrix composites (CMCs). This type of material holds great near-term promise to be used in propulsion system applications. For example, the higher operating temperatures that can be maintained with CMC components result in significantly decreased weight and increased performance. However, most CMCs are very brittle, and their fracture behavior must be well-understood before they can be utilized in flight vehicle structure.

Figures 3 and 4 illustrate two common modes of crack propagation in laminated, bidirectionally reinforced CMC materials. Figure 3 illustrates the case where the initial notch is perpendicular to the lamination plane. In this case, fracture will generally continue in a predominantly mode I manner. The toughness of the composite in this failure mode is strongly influenced by the micromechanisms that occur in the tip and wake regions. These mechanisms include fiber/matrix debonding, matrix cracking, fiber cracking and frictional dissipation during fiber pullout. Figure 4 illustrates the case where one or more outer layers have been notched and the crack front is parallel to the plane of lamination. Under mechanical or thermomechanical loading, the initial flaw will generally propagate through the relatively brittle matrix of the 90 layer; thereafter, failure often proceeds by delamination along the 0/90 interface. Similar to the fracture mode illustrated in Figure 3, the toughness of this interface is influenced by the toughness of the matrix; the orientation, material properties, and bond strength of the fibers; and by the micromechanisms that occur both ahead of the crack and in the delamination wake. The most predominant of these mechanisms are fiber bridging and interface shifting.

The common problem in characterizing and predicting fracture in CMC materials involves the size of the damage zone. This zone may be divided up into the process zone, defined to be that region ahead of the crack front, and the bridging zone, defined to be that portion in the crack wake. For many CMC materials, the bridging zone can be quite large compared to the physical dimensions of the test specimen. That is, due to their high cost, it is generally true that only relatively small sample sizes of CMC materials are available for testing. When the damage zone is large compared to any of the characteristic dimensions of the test sample, the common assumption

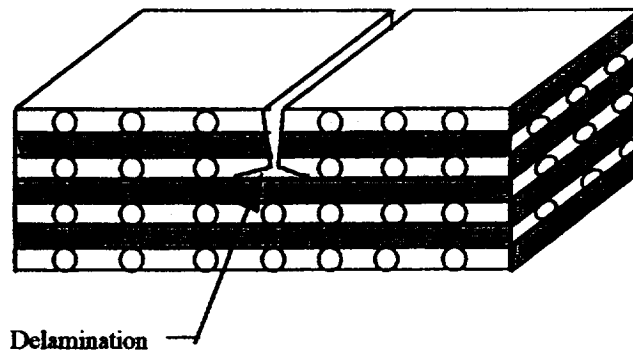


Figure 4: Laminated CMC fracture when crack front is parallel to the plane of lamination.

of small scale damage that is made in linear elastic fracture mechanics is violated. Thus, somewhat specialized data reduction and fracture prediction techniques are required for these materials.

The solid mechanics and materials research at the Syracuse Center for Hypersonics concentrates on developing predictive methodologies for the two types of fracture illustrated in Figures 3 and 4. These two parallel and complementary efforts each involve the development of an analytical model to predict fracture. Both models require a limited amount of input from experiments on relatively standard test coupons. Both models are to be applied and verified at room temperature and at elevated temperatures.

The fracture mode illustrated in Figure 3 is analyzed through a fiber bridging model. Experimental input, necessary to determine the constitutive behavior of the bridging zone, is obtained through three point bending tests. Model verification is performed by comparison of predicted to observed results for three-point bending specimens of different geometries (span length, crack length, etc.), four-point bending specimens, and edge-cracked tension specimens. The fracture mode illustrated in Figure 4 is analyzed using a crack tip element analysis and the associated procedure recently described for laminated materials that may exhibit large damage zones.

## 8 NASA/Syracuse University Center Publications

- [1] Spina, E.F., LaGraff, J.E., Davidson, B.D., Bogucz, E.A., and Dang, T.Q. 1995 "Research and educational initiatives at the Syracuse Center for Hypersonics," AIAA Paper 95-6107, presented at the AIAA 6th International Aerospace Plane and Hypersonic Technologies Conference, Chattanooga, TN.
- [2] McGinley, C.B., Spina, E.F., and Sheplak, M. 1994 "Turbulence Measurements in a Mach 11 Helium Boundary Layer," AIAA Paper 94-2364, presented at the 25th AIAA Fluid Dynamics Conference, Colorado Springs, CO.
- [3] Spina, E.F. and McGinley, C.B. 1994 "Constant-Temperature Anemometry in Hypersonic Flow - Critical Issues and Recent Results," *Experiments in Fluids*, 17, pp. 365-374.
- [4] Sheplak, M., Spina, E.F., and McGinley, C.B. 1994 "Hot-Film Anemometry in Hypersonic Flow," AIAA Paper 94-2232, presented at the 25th AIAA Fluid Dynamics Conference, Colorado Springs, CO.
- [5] Sheplak, M., Spina, E.F., and McGinley, C.B. 1995 "Dynamic characterization of a hot-film probe for hypersonic flow," AIAA Paper 95-6110, presented at the AIAA 6th International Aerospace Plane and Hypersonic Technologies Conference, Nashville, TN.
- [6] Sheplak, M., Spina, E.F., and McGinley, C.B. 1995 "Progress in hot-film anemometry in hypersonic flow," submitted to *Experiments in Thermal and Fluid Sciences*.

- [7] Sheplak, M. 1995 "Design, validation, and testing of a hot-film anemometer for hypersonic flow," Ph.D. dissertation, Mechanical, Aerospace, and Manufacturing Engineering Department, Syracuse University.
- [8] Sheplak, M., Spina, E.F., and McGinley, C.B. 1995 "Constant-temperature hot-film anemometry in high-speed flow," submitted to *Measurement Science and Technology*.
- [9] Kegerise, M.A. and Spina, E.F. 1996 "A comparative study of constant-voltage and constant-temperature hotwire anemometers in supersonic flow," submitted for the *Fourth International Symposium on Thermal Anemometry*, ASME Fluids Engineering Meeting.
- [10] Cataldi, P. 1995 "Transformation of the Syracuse University LICH tube into a hypersonic facility," M.S. thesis, Mechanical, Aerospace, and Manufacturing Engineering Department, Syracuse University.
- [11] Roe, K., Thakur, R., Dang, T., and Bogucz, E. 1995 "Computation of Streamwise Vorticity Injection in High-Speed Shear Layers using Massively Parallel-Architecture Computers," AIAA Paper 95-6111, presented at the AIAA 6th International Aerospace Plane and Hypersonic Technologies Conference, Nashville, TN.
- [12] Campuzano, M. and Dang, T. 1995 "Numerical Study of Lobe-Mixer Fuel-Injection Strut in Scramjet Engine," AIAA Paper 95-2449, 31st Joint Propulsion Conference and Exhibit, San Diego, CA.
- [13] Fox, G., Hawick, K., Haupt, T., Bogucz, E. and Roe, K. 1995 "Application of High Performance Fortran," Northeast Parallel Architectures Center (NPAC) Technical Report No. SCCS 727, Syracuse University.
- [14] Qiu, X., Bordawekar, R. and Dang, T. 1996 "Performance of a 3-D mixing-layer code in High Performance Fortran," to be presented at the Parallel CFD 96 Conference, May 1996.
- [15] Roe, K. and Mehrotra, P. 1995 "Experience with HPF for simple CFD problems," to be published as NASA ICASE technical report.
- [16] Roe, K., Mehrotra, P. and O'Halleron, D. 1995 "Efficiency of HPF parallel loop," to be published as NASA ICASE technical report.
- [17] Roe, K. and Haupt, T. 1995 "Performance of the acoustic wave propagation problem in High Performance Fortran," Northeast Parallel Architectures Center (NPAC) Technical Report No. SCCS 700, Syracuse University.
- [18] Lewalle, J., McGinley, C., and Joe, C. 1995 "Wavelet analysis of turbulence data from a Mach 11 helium boundary layer," manuscript in preparation.
- [19] Levy, A.J. 1995 "Interfacial decohesion and the effective dilatational response of fiber-reinforced composites," accepted for publication by the *Journal of Applied Mechanics*.

## 9 Acknowledgements

Primary funding for the Syracuse University Center for Hypersonics is provided by NASA Headquarters through grant NAGW-3713, monitored by Dr. Isaiah Blankson. Additional funding for hypersonics research has been provided by NASA-Langley Research Center through grants NAG-1-1400 (monitored by Stephen K. Robinson and Michael J. Walsh), NGT-51171 (monitored by Michael J. Walsh), and NGT-70380 (monitored by Griffin Y. Anderson). The undergraduate co-operative education assignments have been supported by Calspan (Dr. Michael Holden), GASL (Dr. John Erdos), Naval Surface Warfare Center (Dr. William Yanta and Dr. Robert Voisinet), and the NASA/Cornell University Space Grant Consortium. Undergraduate research has been partially funded by NSF through grant EEC-9300414 and by the G.E. Foundation.

Appendix	I	- Center for Hypersonics Brochure
Appendix	II	- Announcement – Undergraduate Certificate in Hypersonics
Appendix	III	- Students Working with Center for Hypersonics
Appendix	IV	- Executive Summary of Original Proposal to Office of Aeronautics – NASA Headquarters

# Appendix I

# Syracuse University



# Center For Hypersonics



**Barry D. Davidson**  
Assistant Professor  
Solid Mechanics/Materials Group Leader

- Fracture Mechanics Testing of Ceramic Matrix Composites
- Micromechanical Analysis of Ceramic Matrix Composites
- Static and Fatigue Testing of Materials at Elevated Temperatures

**Geoffrey C. Fox**  
Professor and Director  
Northeast Parallel Architectures Center

- Numerical Methods for Parallel Computers
- Multidisciplinary Analysis & Design
- Industrial Applications

**Hiroshi Higuchi**  
Associate Professor

- Experimental Fluid Dynamics
- Scientific Visualization
- Computer-aided Education

**Alan Levy**  
Associate Professor

- Micromechanics of Materials
- Constitutive Modeling of High Temperature Materials
- Dynamical Systems and Non-linear Oscillations

**Jacques Lewalle**  
Associate Professor

- Turbulence Theory and Modeling
- Wavelet Analysis
- Multiphase Flows

**Volker Weiss**  
Professor  
Chair, Department of Mechanical, Aerospace & Manufacturing Engineering

- Mechanical Behavior of Materials
- Fracture Mechanics Fatigue/NDE
- Deformation Processing

## For more information, contact:

Syracuse University Center for Hypersonics  
Syracuse University  
Engineering & Computer Science  
151 Link Hall  
Syracuse, New York 13244-1240  
315-443-2618 fax 315-443-9099  
email: [su\\_hyper@mars.mae.syr.edu](mailto:su_hyper@mars.mae.syr.edu)

# Appendix II

\*\*\*\*\* ANNOUNCEMENT \*\*\*\*\*

## UNDERGRADUATE CERTIFICATE IN HYPERSONICS

As part of the NASA/Syracuse Center for Hypersonics, a special certificate program has been established for undergraduates in the Mechanical, Aerospace, and Manufacturing Engineering Department. This special course of study will provide students with the background to pursue graduate education in hypersonics or to assume an entry-level position in industry or government dealing with research, development, and policy in the hypersonics field.

The certificate is earned by completing twelve credits of coursework and hypersonic research projects, and is presented at the end of the senior year. Students must complete the following courses:

- AEE-441 *Introduction to Compressible Fluid Mechanics*
- AEE-491 *Hypersonics Research Project*
- Two "hypersonics electives" chosen from:
  - AEE-436 *Composite Materials*
  - AEE-443 *Introduction to Computational Fluid Dynamics*
  - AEE-492 *Hypersonics Research Project II*
  - AEE-542 *Elements of Hypersonic Flight*

Most students will enter the certificate program as they complete AEE-441 in their junior year, with most course and research work being done in the senior year. In most cases, the Hypersonics Certificate can be earned with an overload of only 3 credits. The certificate program should be declared before the end of the junior year. Contact Prof. Eric F. Spina (143 Link Hall) for further details.

# Appendix III

## Students Covered by The Syracuse University Center for Training and Research in Hypersonics

Student Name	BS Degree	Year	MS Degree	Year	Ph.D Degree	Year
Ballaro, Charles	Aerospace	1994			Aerospace	not awarded yet
Bhandari, Ajay	Mechanical	1997				
Biagioni, Leonardo					Mech and Aero	not awarded yet
Blake, Carl			Aerospace	1997		
Bordawekar, Rajesh			Comp Engineering	1993	Comp Engineering	1996
Cataldi, Paolo	Aerospace	1993	Aerospace	1995		
Chrisochoides, Nikos						Post-Doc
Degani, Amar						Post-Doc
Draisey, Michael			Comp Engineering			Visiting Fellow
Hardikar, Kedar			Mechanical	1997		
Hassan, Ricardo						Visiting Fellow
Henning, Garth	Aerospace	1996				
Hudson, Ryan	Aerospace	1995	Mechanical	1997		
Kegerise, Michael	Mechanical	1994	Mechanical	1996	Mech and Aero	2000
Mazzarella, James	Mechanical	1993			Mech and Aero	not awarded yet
McMahon, Michael	Mechanical	1998				
Nill, Laurie	Aero and Astro	1993			Aerospace	not awarded yet
Polaha, Jonathon	Aerospace	1994	Mechanical	1997		
Qiu, Xuwen			Comp Engineering Mechanical	Sum 1998 Fall 1997	Mechanical	1999
Roe, Kevin			Aerospace	1996		
Sabino, Deo	Aerospace	1994	Mechanical	1996		

Sanders, Erica	Mechanical	1997					
Sealy, Michael			Aerospace	1996			
Sheplak, Mark	Mechanical	1989	Mechanical	1992	Mechanical	1995	
Sherwood, Tor W.	Aerospace	1995	Mechanical	1997			
Thakur, Rajeev			Comp Engineering	1992	Comp Engineering	1995	
Van Eck, Anne						Visiting Fellow	
Wang, Yu	Aerospace	1985	Comp Engineering Aerospace	1999 1989	Comp Engineering Mech and Aerospace	not awarded yet not awarded yet	

# Appendix IV

## 2. EXECUTIVE SUMMARY

The Department of Mechanical, Aerospace, and Manufacturing Engineering and the Northeast Parallel Architectures Center of Syracuse University offer a plan to establish a training and research program with the prime objective of producing the next generation of leaders in the field of hypersonics. This goal will be achieved through a comprehensive five-year program that includes elements of undergraduate instruction, advanced graduate coursework, undergraduate research, and leading-edge hypersonics research.

The instruction and research are designed to impact three areas of critical importance in hypersonics: fluid dynamics/propulsion, solid mechanics/materials, and multidisciplinary analysis and design via high-performance computing. Funded undergraduate and graduate research programs exist at Syracuse University in each of these areas. Undergraduate and graduate courses will be developed and enhanced to provide fundamental instruction in the major principles of hypersonics. As a complement to curriculum development activities, two texts are proposed for graduate training, and multi-media courseware is proposed to aid instruction of fundamentals related to hypersonics. Three highly successful undergraduate research programs (all funded by the National Science Foundation) will be integrated into the training efforts of the Syracuse Hypersonics Center, with a primary goal being to encourage promising undergraduates to attend graduate school for hypersonics.

The advanced research performed in the Center will have several different components: experimental research on a number of turbulence-dominated aerodynamic phenomena, computational fluid dynamics research at Syracuse University's state-funded Northeast Parallel Architectures Center (NPAC), computational and experimental research on advanced high-temperature materials, and research on methods to enable structural and fluid-dynamic design issues to be considered simultaneously via high-performance (parallel) computing. Collaborative research activities with Wright Aeronautical Laboratory and NASA-Langley are proposed using an existing collaboration between the principal investigator and NASA-Langley as a model. Students working within the Syracuse Center will use unique national facilities at Langley and Wright Labs, thereby enhancing both the overall research effort and student development.

The Syracuse Hypersonics Center will initially include research and training contributions from twelve faculty and two post-doctoral fellows. Syracuse University is strongly committed to the efforts of these faculty as illustrated by its willingness to provide a 2:1 match to NASA funds for the Hypersonics Center. The contribution includes the establishment of two Syracuse University Hypersonics Fellowships reserved for under-represented groups, two additional graduate research assistantships to integrate high-performance computing into the Center's activities, academic-year release time for faculty to develop new courses and course material for hypersonics instruction, and a variety of other funds for graduate tuition, travel, and equipment.